Advanced imaging and planning for proton therapy

Joint Symposium at PTCOG 2018 – Cincinnati, US

Aymeric Harmant – Marketing Director IBA
Todd Deterding – Pinnacle Marketing Director Philips
Access the best-in-class radiation oncology solutions through our combined expertise

47 Rooms in operation
4 Rooms in development

5 Rooms in operation
22 Rooms in development

116 IBA PT Rooms
50 IBA PT Centers

30 Iba + PHILIPS PT Centers
Understanding your challenges

Improving outcomes while minimising side effects

Managing multiple technologies

Boosting capacity, reducing staff workload

Reducing stress, increasing patients peace of mind,
Efficient workflow & better patient experience

Open gantry design

Faster patient set-up

Comfort for clinical staff

Philips Ambient Experience
Precise treatment

Cone Beam CT on a gantry with largest field of view at isocenter
Integrated solution
Integrated solution

- adaPT
- Mosaiq
- Pinnacle
- Ingenia MR-RT
- IQon Spectral CT
What you will learn at the symposium

Monoisocentric intensity modulated proton therapy for bilateral breast cancer
Marcio Fagundes, MD

Commissioning and planning optimization for open IMPT gantries
Jamil Lambert, PhD

MRI for planning and on-therapy monitoring of proton therapy patients
Chia-ho Hua, PhD
Marcio Fagundes, MD

Medical Director, Radiation Oncology, Miami Cancer Institute

Monoisocentric intensity modulated proton therapy for bilateral breast cancer
Innovations in Proton Therapy

Monoisocentric Intensity Modulated Proton Therapy (IMPT): An Innovative Technique for Bilateral Chest Wall and Regional Nodal Radiotherapy
Of course there’s the beach...
Disclosures: none
THE PAST: 2011-2012, Before PBS technique
we used uniform scanning for breast treatment
Limited field size = requires multiple fields and match lines

- Supraclavicular and axilla LN field
  - Field edge
  - Match line

- Chest wall and IMC LN field

  - Long treatment time + 45 min
  - Higher skin dose then PBS
  - Match lines subject to hot or cold spots
  - ....
A Novel Approach to Postmastectomy Radiation Therapy Using Scanned Proton Beams

Nicolas Depauw, MS, Estelle Batin, PhD, Julianne Daartz, PhD, Anatoly Rosenfeld, PhD, Judith Adams, BS, Hanne Kooy, PhD, Shannon MacDonald, MD, and Hsiao-Ming Lu, PhD

*Francis H. Burr Proton Therapy Center, Department of Radiation Oncology, Massachusetts General Hospital, Boston, Massachusetts; and Centre for Medical Radiation Physics, University of Wollongong, New South Wales, Australia
Advances in Breast Cancer

Our very first breast proton patient should be treated with an innovative method

Monoisocentric Intensity Modulated Proton Therapy (IMPT): An Innovative Novel Technique for Bilateral Chest Wall and Regional Nodal Radiotherapy

Department of Radiation Oncology
Marcio Fagundes, Jen Yu, Kevin Greco, Craig McKenzie, Jaafar Bennouna, Alonso Gutierrez and Minesh Mehta
83 y.o. female patient with bilateral breast cancer ER/PR+, Her-2 -, post bilateral mastectomy, axillary dissection:

- Left breast pT2N1 2.5 cm invasive ductal carcinoma (IDC), UOQ, 2/19 +LN;
- Right breast pT2N2a IDC 3.4 cm UIQ, 6/12 + LNs.
- PR after neoajuvant AC x 4

PMHx: DM, CAD, smoking x 17 yrs, COPD, NED from stage I NSCLC s/p left lingula segmentectomy.

**Recommendation:**
50.4 Gy to bilateral chest wall, axilla, sclav regions and right IMC

**Goal was to achieve a proton plan:**
- Target coverage
- OAR sparing
- Efficient delivery
Monoisocentric IMPT plan with gradient junction using 3 fields
IMPT plan and gradient junction
## IMPT: Coverage and Constraints

<table>
<thead>
<tr>
<th>Metric</th>
<th>IMPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target coverage:</td>
<td>D99 50.4 Gy</td>
</tr>
<tr>
<td>Mean heart dose:</td>
<td>0.06 Gy</td>
</tr>
<tr>
<td>LAD:</td>
<td>D1 0.47 Gy, Mean 0.09 Gy</td>
</tr>
<tr>
<td>Total lung:</td>
<td>V20 8%, V5 21%</td>
</tr>
<tr>
<td>Esophagus:</td>
<td>D1 29.8 Gy, Mean 4.2 Gy</td>
</tr>
</tbody>
</table>

Marcio Fagundes, MD MCI – Miami Cancer Institute
Robustness Evaluation

- 8 scenarios: 6 Pt setup errors (5mm, ±x, ±y, ±z) &
- 2 range uncertainties (±3.5%)
- Nominal and 2 worst case scenarios are illustrated:

Coverage was maintained D99CTV > 95% of prescribed dose
Quality Control Scans During Treatment

Plan

QA CT scans

Nominal Dose  Week 1  Week 3

No hot spots

Reproducible coverage and OAR sparing
Patient Setup
Imaging and Monitoring

- C-RAD
- KV/KV imaging with skin surface fiducials
- CBCT

C-RAD
Patient treatment setup and monitoring

Orthogonal X-rays
Surface BBs for correlation

Marcio Fagundes, MD MCI – Miami Cancer Institute
Patient Setup CBCT

Planning CT

CBCT
Patient Setup CBCT
Fused planning CT and CBCT
C-RAD

Patient treatment setup and monitoring

Note: the time shown in this figure is consistent with what we quoted in ASTRO abstract: The average treatment time per fraction, which included the pre-treatment imaging for setup, during treatment imaging for verification and proton beam delivery of all fields, was 29:30 min (range from 17:26 to 69:06)

Monitoring during beam on

Treatment fraction completed in 21 minutes

Highly efficient pre-treatment imaging and delivery

Marcio Fagundes, MD MCI – Miami Cancer Institute
Skin Tolerance

Evidence of midline junction skin sparing

Marcio Fagundes, MD MCI – Miami Cancer Institute
Miami Cancer Institute = Comprehensive Technology
A True Multimodality Approach (multiple platforms)

We can create proton backup plans for the best suited equipment for any given disease
## Tomotherapy backup plan

<table>
<thead>
<tr>
<th></th>
<th>IMPT</th>
<th>Tomo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target coverage:</strong></td>
<td>D99 50.4 Gy</td>
<td>50.4 Gy</td>
</tr>
<tr>
<td><strong>Mean heart dose:</strong></td>
<td>0.06 Gy</td>
<td>7.5 Gy</td>
</tr>
<tr>
<td><strong>LAD:</strong></td>
<td>D1 0.47 Gy</td>
<td>26.7 Gy</td>
</tr>
<tr>
<td></td>
<td>Mean 0.09 Gy</td>
<td>16.2 Gy</td>
</tr>
<tr>
<td><strong>Total lung:</strong></td>
<td>V20 8%</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>V5 21%</td>
<td>87%</td>
</tr>
<tr>
<td><strong>Esophagus:</strong></td>
<td>D1 29.8 Gy</td>
<td>33 Gy</td>
</tr>
<tr>
<td></td>
<td>Mean 4.2 Gy</td>
<td>11 Gy</td>
</tr>
</tbody>
</table>

**Patient completed proton treatment uneventfully without any downtime**

Marcio Fagundes, MD MCI – Miami Cancer Institute
Challenges in Treating Bilateral Breast Cancer with IMPT:

- Patient setup (posture correction-arms) C-RAD
- Field Junctions IMPT
- Intrafraction Motion monitoring C-RAD
- Daily reproducibility Daily kV/C-RAD
- Changing Anatomy Weekly QA CT
- Treatment time:
  - Reduced with single isocenter
THANK YOU

Marcio Fagundes, MD
Medical Director – Radiation Oncology
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Baptist Health South Florida

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786-527-8140
Jamil Lambert, PhD

Senior Physicist, Rutherford Cancer Centre South Wales

Commissioning and planning optimization for open IMPT gantries
### RCC Sites

<table>
<thead>
<tr>
<th>Location</th>
<th>Centre open (linac, CT, MR, chemo)</th>
<th>Proton go-live</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newport</td>
<td>March 2017</td>
<td>April 2018</td>
</tr>
<tr>
<td>Newcastle</td>
<td>June/July 2018</td>
<td>Q2 2019</td>
</tr>
<tr>
<td>Reading</td>
<td>July/Aug 2018</td>
<td>Q4 2019</td>
</tr>
<tr>
<td>Liverpool</td>
<td>Q2 2019</td>
<td>Q3 2020</td>
</tr>
</tbody>
</table>

**Plus** another 4 centres in UK
**IBA ProteusOne**

- Synchrocyclotron with superconducting coil: “S2C2”
- 230MeV pulsed proton beam, high dose per pulse

- 220° gantry
- proton pencil beam scanning
- 20x24cm field size

- cone-beam CT & oblique Xray
- ‘open feel’ treatment room
- Philips ambient experience

- Engineer support in Control Room with treatment staff
Our Timeline

2015  Feb  Proton Partners International began – raise funding, recruit team

2016  Apr  begin building in Newport

2017  Mar  open Newport centre, regulator approval to commence radiotherapy treatment

2017  Apr  proton gantry delivered to Newport

2017  May  cyclotron delivered to Newport

2018  Feb  commence acceptance tests and clinical commissioning

2018  Mar  regulator approval to commence proton therapy treatment (inc paediatrics)

2018  Apr 10th  first proton therapy treatment

2018  June  complete phase 2 of clinical commissioning (complex treatments)
Our Timeline

4 April 2017
https://www.youtube.com/watch?v=Xlak-lggej4

20 May 2017
https://youtu.be/jX6tNd0AlU
Commissioning prior to ‘machine-time’

- Philips Pinnacle TPS
  - First clinical users – excellent support from Philips and IBA
  - Proton pencil beam scanning clinical release Jan 2017 – a year of testing prior to machine commissioning
    - Modelled beam with Nice data > delivered fields on Proteus One in Nice
    - Tested PBS optimisation and export to Mosaiq
  - Beam modelling can be done by user, multiple beam models allowed
- One beam model with a geometrically model the range-shifter can lead to larger inaccuracies in the dose calculation
- Creation of a separate beam model for the range-shifter should theoretically improve the dose calculation accuracy
## Acceptance & Commissioning process (8 weeks)

<table>
<thead>
<tr>
<th>Machine time (double shifts, RCC, IBA, NPL physicists)</th>
<th>Additional (Philips, RCC physicists)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Acceptance Tests &amp; beam data for Treatment Planning System</td>
<td></td>
</tr>
<tr>
<td>Safety Acceptance Tests</td>
<td>Beam data modelling in TPS (no range-shifter), initial beam model used to create verification fields</td>
</tr>
<tr>
<td>Imaging Acceptance Tests &amp; clinical setup of CBCT</td>
<td></td>
</tr>
<tr>
<td>Calibrate QA devices</td>
<td></td>
</tr>
<tr>
<td>Verification fields delivered/measured</td>
<td>Refine beam data model in TPS</td>
</tr>
<tr>
<td>Absolute dose (TRS398) measurements (energy layers) for TPS</td>
<td>Recalculate verification fields and compare to measurements</td>
</tr>
<tr>
<td>Measure WET for immobilisation devices etc.</td>
<td></td>
</tr>
<tr>
<td>Setup daily QA, patient QA</td>
<td></td>
</tr>
<tr>
<td>Absolute dose (TRS398) in dose cubes created in TPS using PPC05 &amp; Roos chambers</td>
<td>Range-shifter beam data modelling on TPS</td>
</tr>
<tr>
<td>External dose audit (WPE)</td>
<td></td>
</tr>
<tr>
<td>Clinical Applications training, workflows, end-to-end testing</td>
<td></td>
</tr>
<tr>
<td>First treatment (SFUD, no range-shifter)</td>
<td></td>
</tr>
</tbody>
</table>
Commissioning measurements for Pinnacle TPS

- Integral depth dose curves (Bragg peaks)
  - Measured every 5 MeV from 70 MeV to 226.2 MeV without range shifter, and from 80 MeV with the range shifter (62 IDDs)
- In air fluence
  - x & y profiles of central spots, measured every 5 MeV from 70 MeV to 226.2 MeV at +20, +10, 0, -10, -20 cm from isocentre
- Absolute dose
  - Dose at two depths for a 10x10 single energy layer, every 5 MeV, with & without range-shifter
- Machine Characteristics
  - SAD x (cm), SAD y (cm); max beam deflection at iso (cm); min spot MU limit;
  - Max and min energy limits; max and min snout extension (cm);
  - Range-shifter physical thickness; range-shifter WET
Commissioning measurements for Pinnacle TPS

• Integral depth dose curves (Bragg peaks)
  • Measured every 5 MeV with and without range-shifter
Commissioning measurements for TPS

Pinnacle fit of 160MeV Bragg Peak
Commissioning measurements for Pinnacle TPS

• In air fluence
  • x & y profiles of central spots, measured every 5 MeV from 70 MeV to 226.2 MeV at +20, +10, 0, -10, -20 cm from isocentre
  • Measured with Lynx scintillator
Commissioning measurements for Pinnacle TPS

- In air fluence
  - x & y profiles of central spots, measured every 5 MeV from 70 MeV to 226.2 MeV at +20, +10, 0, -10, -20 cm from isocentre
Commissioning measurements for Pinnacle TPS

Spot sigma as a function of energy at isocentre in air
Commissioning measurements for Pinnacle TPS

Absolute dose
- Dose was measured at 2 depths for a 10x10 single energy layer, measured every 5 MeV
- Measured with and without range shifter
- Shown here is the dose at 2 cm depth without a range shifter
Pinnacle beam model validation

Verification field measurements

- Used a script to create multiple cubic fields with different range, modulation, field size, spot spacing etc.
- Created a small representative subset and measured
  - Absolute dose
  - Depth dose with Zebra
  - Profiles with MatriXX and Lynx
Verification field measurements

- Average of the absolute dose was shifted
- No trend with range
- Corrected by scaling the dose for every energy in the beam model by the same factor

**Graph:**
- X-axis: Measurement number
- Y-axis: Difference between measured and Pinnacle dose at isocentre (%)

**Legend:**
- Blue dots: 1st iteration
Pinnacle beam model validation

Verification field measurements

- Separate beam model for the range shifter
- Absolute dose within 2% for the range shifter fields
Pinnacle beam model validation

Verification field measurements

- Measurement of a field with a large spot spacing at 2cm depth
- Shows a problem with the spot size in the beam model
Pinnacle beam model validation

Verification field measurements

• Coordinate system used by IBA and Philips is different

• Caused the distance from isocentre to be flipped in the first iteration beam model spot profiles

• After correction of ± sign in the distance from iso the profiles match
Pinnacle IMPT Dose Calculation

• Improvements implemented vs previous ‘analytical’ algorithms. Accounting for density changes lateral to each spot

• Pinnacle subdivides the contribution of the single Gaussian component into many sub spots. For accurate corrections of heterogeneities lateral to the spot’s central axis
  • Large number of sub-spots, typically ~300
  • Pinnacle$^3$ computes laterally 4 sigma for the primary fluence to capture 99.994% of the dose
  • The sub spot doses are stored in memory and do not need to be recalculated for each run of the optimiser.
Pinnacle IMPT Dose Calculation

- Pinnacle\(^3\) does not use the water equivalent thickness (WET) to find the lateral scatter.

- The Multiple Coulomb Scattering (MCS) is calculated at every step along each pencil as an independent calculation that is the total scatter contribution of all materials that occurred previously.

- Important for lung planning
  - Previous algorithms don’t accurately calculate the difference in scatter at the surface of the lung and the exit of the lung

- In Pinnacle\(^3\) the dose deposition kernel for each pencil at each dose step is calculated based on material, residual energy, and previously encountered materials.
  - The scattering for each pencil can be more accurately determined per pencil per step
Pinnacle IMPT Dose Calculation

• Calculated Scatter is dependent on:
  • The order of the materials ‘upstream’
  • Distance from the calculation plane

• The MCS is calculated in 2 mm steps in depth dropping to 1 mm near the Bragg Peak

• The density is used to find the scattering power of each voxel. The stopping power is used to find the ‘residual’ energy of the proton entering that voxel

\[
\sigma^2(z) = (z - z_1)^2 \theta_1^2 + (z - z_2)^2 \theta_2^2 \\
\sigma^2(z_j) = \sum_{i<j} (z_j - z_i)^2 \theta_j^2
\]
First patient treatment 10/04/18

- Prostate treatment
  - 60 CGE in 20#
  - Two lateral fields, ‘single-field uniform dose’
  - Rectal Spacer, “Bio-Protect” balloon
  - Endo-rectal balloon

- Daily image guidance with CBCT and 6D correction
Acknowledgements

• John Pettingell – Chief Physicist & Head of Radiotherapy
• Jo Clorley – RCC senior physicist
• Laertes Papaspyrou – Philips clinical scientist
• Nigel Deshpande – Philips clinical scientist
• IBA project team and site team and IBA commissioning physicists
• Russell Thomas & National Physical Laboratory team
Chia-ho Hua, PhD

Physicist, St. Jude Radiation Oncology

MRI for planning and on-therapy monitoring of proton therapy patients
MRI for Planning and On-therapy Monitoring of Proton Therapy Patients

Chia-ho Hua, PhD
St. Jude Children’s Research Hospital
Memphis, Tennessee, USA
The 57th Annual PTCOG meeting, May 25, 2018
Conflict of interest disclosures

• Research collaboration with Philips Healthcare on spectral CT and MRI
• Reimbursed by Philips for travel and meeting expenses
What I will present

• Our MRI system installation, training, and process to go live
• Image quality with MR coils in RT configurations
• Our MR simulation and on-therapy imaging workflow
• How do other institutions use MRI for RT?

What I will not cover

• Technical commissioning and routine QA program (white paper)
• Financial aspects
• Specific applications on adult proton therapy
St. Jude Red Frog Events Proton Therapy Center

Proton Therapy Center (1st patient in 2015)

Pencil beam scanning IMPT

Volumetric image guidance with robotic CBCT

3 Treatment Rooms

Gantry

Fixed
Dedicated MRI systems in our radiation oncology department

2004-2012
Philips 0.23T Panorama
Open MRI
Resistive magnet

2012-2016
Scimedix 1.5T SM160
60-cm closed bore
Liquid helium refill

2016-present
Philips 3T and 1.5T Ingenia
70-cm wide bore
zero boil off
3T in proton therapy center
## Advantages and challenges: dedicated MRI systems in RO departments

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Visualize tumors/resection cavities at the time of RT</td>
<td>• Financial investment and revenue</td>
</tr>
<tr>
<td>• Patients imaged in treatment position</td>
<td>• Converting an existing room (RF shielding, quench pipe)</td>
</tr>
<tr>
<td>• Visualize critical organs (optic chiasm, brainstem, hippocampus, ovaries, etc)</td>
<td>• More equipment to manage – staff with MR expertise?</td>
</tr>
<tr>
<td>• Flexibility of patient and staff scheduling</td>
<td>• Steep learning curve for therapists</td>
</tr>
<tr>
<td>• On-treatment MRI easier (detect tumor shape changes earlier)</td>
<td>• Country or state requirements of MRI technologist qualification (need for a MR technologist?)</td>
</tr>
<tr>
<td>• Flexibility to edit pulse sequences and ensure high spatial fidelity</td>
<td></td>
</tr>
<tr>
<td>• Ample research opportunities</td>
<td></td>
</tr>
</tbody>
</table>
Scheduled 1 week to decommission existing MR system

2 weeks for installing new MR (installation, calibration, configuration)

1 week for acceptance testing by physicists

2-3 weeks handover (build scan protocols, safety, volunteer scanning, patients)

Therapists received online MRI training and off-site trainings in Cleveland prior to on-site training/go live

Multiple follow-up visits by clinical specialists (training, refine scan protocols)

Upgrade, new pulse sequences
<table>
<thead>
<tr>
<th>Test Name</th>
<th>Institution-Defined Performance Criteria and Methods</th>
<th>Measured Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips IATD tests</td>
<td><strong>Criteria:</strong> Per Philips passing criteria</td>
<td>Passed</td>
</tr>
<tr>
<td></td>
<td><strong>Method:</strong> Philips internal methods</td>
<td></td>
</tr>
<tr>
<td>B0 magnetic field</td>
<td><strong>Criteria:</strong> Inhomogeneity ≤ 0.45 ppm \text{ max} for 40-cm DSV, ≤ 0.08 ppm \text{ max} for 30-cm DSV, ≤ 0.022 ppm \text{ max} for 20-cm DSV</td>
<td>1.5T: 0.29 ppm \text{ max} for 40-cm DSV, 0.07 ppm \text{ max} for 30-cm DSV, 0.021 ppm \text{ max} for 20-cm DSV</td>
</tr>
<tr>
<td>homogeneity</td>
<td><strong>Method:</strong> 24 plane homogeneity plot after final shimming during installation</td>
<td>3T: 0.35 ppm \text{ max} for 40-cm DSV, 0.052 ppm \text{ max} for 30-cm DSV, 0.008 ppm \text{ max} for 20-cm DSV</td>
</tr>
<tr>
<td>Magnetic field drift</td>
<td><strong>Criteria:</strong> Drift ≤ 1 ppm/day</td>
<td>1.5T: ~0.40 ppm/day (1 ppm = 63.9 Hz)</td>
</tr>
<tr>
<td></td>
<td><strong>Method:</strong> Record the center frequency determined by morning Periodic Image Quality Test (PIQT) quality assurance for a period of 14 days.</td>
<td>3T: ~0.16 ppm/day (1 ppm = 128 Hz)</td>
</tr>
<tr>
<td>Geometric accuracy</td>
<td><strong>Criteria:</strong> Inaccuracy ≤ 1 mm for 32-cm DSV</td>
<td>For 1.5T and 3T: ≤1 mm for 32-cm DSV, except at bottom edge of phantom, possibly due to susceptibility effect from plastic-to-air interface</td>
</tr>
<tr>
<td></td>
<td><strong>Method:</strong> ACR geometric accuracy method and Philips MR-RT geometric distortion phantom analysis</td>
<td></td>
</tr>
<tr>
<td>High-contrast spatial</td>
<td><strong>Criteria:</strong> 1-mm hole size should be resolved</td>
<td>For 1.5T and 3T: 1-mm holes were resolved</td>
</tr>
<tr>
<td>resolution</td>
<td><strong>Method:</strong> ACR phantom and method</td>
<td></td>
</tr>
</tbody>
</table>
Patient imaging with immobilization devices and coils in RT configurations

<table>
<thead>
<tr>
<th>Site</th>
<th>Receiver coil*</th>
<th>Typical FOV (mm²)</th>
<th>Protocol†</th>
<th>Typical intrinsic resolution‡ (mm³)</th>
<th>Typical band width (Hz/pixel)</th>
<th>Typical scan time (min)</th>
<th>Typical TR/TE (ms)</th>
<th>Typical flip angle (degrees)</th>
<th>Typical SENSE factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large FOV</td>
<td>Small FOV</td>
<td>Large FOV</td>
<td>Small FOV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brain w/ immobilization devices</td>
<td>Flex L</td>
<td>Flex M</td>
<td>250×200×200</td>
<td>220×180×180</td>
<td>3D T2 TSE</td>
<td>1.0×1.0×2.0</td>
<td>936</td>
<td>5.2</td>
<td>2500/229</td>
</tr>
<tr>
<td></td>
<td>3D T1 TSE</td>
<td>0.9×0.9×1.8</td>
<td>455</td>
<td>6.3</td>
<td>8.0/3.5</td>
<td>8</td>
<td>1.1 × 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3D T1 TFE</td>
<td>0</td>
<td>8</td>
<td>1.1 × 1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3D T2 FLAIR w/ SPIR</td>
<td>1.2×1.2×2.0</td>
<td>1092</td>
<td>6.4</td>
<td>4800/316</td>
<td>40</td>
<td>2.3 × 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3D T2 TSE</td>
<td>0.8×0.8×1.7</td>
<td>797</td>
<td>5.5</td>
<td>2500/259</td>
<td>90</td>
<td>2.9 × 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard head</td>
<td>or 32-channel head</td>
<td>3D T2 TSE</td>
<td>0.9×0.9×1.8</td>
<td>456</td>
<td>3.9</td>
<td>8.0/3.5</td>
<td>8</td>
<td>2.0 × 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3D T2 FLAIR w/ SPIR</td>
<td>1.0×1.0×2.0</td>
<td>936</td>
<td>5.4</td>
<td>4800/354</td>
<td>90</td>
<td>3.0 × 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brain w/o immobilization devices</td>
<td>2D TSE DWI w/ SPIR</td>
<td>0.4×0.6×1.2</td>
<td>108</td>
<td>5.1</td>
<td>235/35</td>
<td>18</td>
<td>2.5 × 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2D EPI DWI w/ SPIR</td>
<td>2.0×2.0×4.0</td>
<td>704</td>
<td>4.9</td>
<td>147/83</td>
<td>71</td>
<td>2.0 × 1.0</td>
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<tr>
<td></td>
<td>2D PCASL w/ SPIR</td>
<td>2×2.5×2.5</td>
<td>32</td>
<td>6</td>
<td>285/84</td>
<td>90</td>
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<tr>
<td></td>
<td>2D SWI</td>
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<td>255</td>
<td>4.5</td>
<td>317/2</td>
<td>17</td>
<td>2.0 × 1.3</td>
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<tr>
<td>Head and neck</td>
<td>or anterior</td>
<td>2D T2 TSE</td>
<td>1.1×1.1×2.4</td>
<td>841</td>
<td>6</td>
<td>2000/213</td>
<td>40</td>
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<tr>
<td></td>
<td>3D T1 TSE</td>
<td>1.1×1.1×2.2</td>
<td>457</td>
<td>5.6</td>
<td>6.6/3.2</td>
<td>8</td>
<td>3.5 × 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3D T1 TFE</td>
<td>0.9×1.2×4.0</td>
<td>461</td>
<td>5.3</td>
<td>2814/100</td>
<td>90</td>
<td>2.0 × 1.0</td>
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<td></td>
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<tr>
<td>Cervical spine</td>
<td>Flex L</td>
<td>Flex M</td>
<td>250×320×250</td>
<td>200×250×200</td>
<td>3D T2 TSE</td>
<td>1.1×1.1×2.2</td>
<td>1084</td>
<td>5.7</td>
<td>2500/227</td>
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<tr>
<td></td>
<td>3D T1 TSE</td>
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<td>455</td>
<td>8.4</td>
<td>8/3.5</td>
<td>8</td>
<td>2.5 × 1.0</td>
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<tr>
<td></td>
<td>3D T1 TFE</td>
<td>1.2×1.2×4.0</td>
<td>461</td>
<td>5.3</td>
<td>2814/100</td>
<td>90</td>
<td>2.0 × 1.0</td>
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<tr>
<td>Thoracic/lumbar spine</td>
<td>Anterior</td>
<td>250×380×380</td>
<td>200×285×285</td>
<td>3D T2 TSE</td>
<td>1.1×1.1×2.2</td>
<td>1084</td>
<td>5.7</td>
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<td>90</td>
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<td>8/3.5</td>
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<td>2814/100</td>
<td>90</td>
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<td></td>
<td></td>
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<tr>
<td>Pelvis</td>
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<td>250×310×250</td>
<td>3D T2 TSE</td>
<td>1.3×1.3×2.6</td>
<td>1.2×1.2×2.4</td>
<td>804</td>
<td>5.5</td>
<td>2200/250</td>
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<td>457</td>
<td>5</td>
<td>7.5/4.2</td>
<td>8</td>
<td>3.5 × 1.0</td>
<td></td>
<td></td>
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<tr>
<td>Abdomen</td>
<td>Anterior</td>
<td>310×390×280</td>
<td>200×300×270</td>
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<td>1.3×1.3×2.6</td>
<td>1.1×1.1×2.2</td>
<td>792</td>
<td>6.1</td>
<td>2200/250</td>
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</table>

Hua, Uh, Krasin, et al. Clinical implementation of magnetic resonance imaging systems for simulation and planning of pediatric radiation therapy. J Med Imag Radiat Sci 2018
Example images with coils in RT configurations (Philips Ingenia 1.5T)

Planning CT and MR images of a 12-year-old patient with craniopharyngioma.

Example images with coils in RT configurations (Philips Ingenia 1.5T)

Planning CT and MR images of a 6-year-old patient with medulloblastoma.
Example images with coils in RT configurations (Philips Ingenia 1.5T)

Planning CT and MR images of a 15-year-old patient with rhabdomyosarcoma.

Example images with coils in RT configurations (Philips Ingenia 1.5T)

Planning CT and MR images of a 17-year-old patient with Ewing’s sarcoma in the knee.

Image quality: 1.5T vs. 3T

3 radiation oncologists reviewed side-by-side 1.5T and 3T MR images for 6 pediatric patients with brain tumors (ependymoma, medulloblastoma, pilocytic astrocytoma, optic pathway glioma, and GBM)

3T had the 5-22% higher grey-white matter contrast (on the superior temporal gyrus)

Physicians reported that 3T had superior performance in

- delineation of cranial nerves and dural/meningeal surfaces
- delineation of areas of residual disease (most apparent in the case of ependymoma at the cranio-cervical junction) and the margins of gross disease (as in the pilocytic astrocytoma and germinoma cases)
- grey-white matter differentiation of cerebellar folia

But advantage is less for tumors that have undergone gross total resection.

Observed increased in chemical shift, susceptibility, and flow artifacts near the brainstem in the 3T cases.
Our clinical workflow

Tumors most imaged with MRI for proton planning in our department are brain tumors (ependymoma, medulloblastoma, craniopharyngioma, pilocytic astrocytoma, brainstem glioma, ATRT, GBM) sarcoma (rhabdomyosarcoma, Ewing sarcoma).

We also image patients with neuroblastoma, Wilms, and Hodgkin disease for assessing motion.
Our clinical workflow

Tumors most imaged with MRI for proton planning in our department are brain tumors (ependymoma, medulloblastoma, craniopharyngioma, pilocytic astrocytoma, brainstem glioma, ATRT, GBM) and sarcoma (rhabdomyosarcoma, Ewing sarcoma).

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On-therapy MRI

- Prescribed based on clinical need by individual radiation oncologists.
- Most imaged were craniopharyngioma, ependymoma, pilocytic astrocytoma, Ewing sarcoma, and rhabdomyosarcoma.
- Using a subset of planning sequences, >95% without contrast administration.
- Main purpose – detect changes in tumor and surgical cavity during the treatment course caused by cyst expansion, tumor progression, cavity volume dynamics after resection, or tumor position shift due to hydrocephalus.
- Other purposes – monitoring potential early effects on normal tissues and anatomic variations along the proton beam paths that may affect the tumor coverage.
How do others use MR for PT patients?

Assessing organ motion as a function of patient setup

Various setups for PT and MRI of pancreatic cancer patients

Surveillance of craniopharyngioma cyst growth during proton therapy

Pancreas stability of 6 different patient setup


How do others use MR for PT patients?

In vivo dosimetric verification of proton end-of-range

Spine MRI 7-51 weeks after proton therapy

Liver MRI 11-25 weeks after proton therapy

Estimating threshold doe for focal liver reaction

Liver Gd-DTPA-EOB MRI after proton therapy


Takamatsu et al. PLOS One December 1 2016.

Selected MRI for RT research at St. Jude
4D MRI research (in-house)

- To replace 4DCT with 4D MRI for pediatric patients
- To assess motion and design ITV margins for patients receiving proton therapy
- A novel technique has been developed which uses non-navigator, image-based internal respiratory surrogate derived by dimensionality reduction (DR)

Dynamic acquisition of each coronal slice.

Dynamic images from 20 slices (thickness, 5 mm) at various respiratory phases are sorted to make a representative 4D MRI at ten respiratory phases.

Evaluation with a digital phantom (XCAT2) showed an excellent match between the DR-derived respiratory surrogate and the gold standard, diaphragm position.

Pediatric organ motion measured with 4D MRI

Proton interplay effect analysis with pediatric organ motion measured with 4D MRI

Pencil-beam scanning to deliver proton therapy is more susceptible than other methods to respiration-induced tumor motion. The 4D MRI data were spatially registered to the static 3D planning CT to assist in the delineating the ITV. For assessing interplay effect, virtual 4D CT were generated by mapping motion fields from 4D MRI data to static 3D CT.

Finding:

1. The interplay effect is not a concern when delivering scanning proton beams to younger pediatric patients with tumors located in the retroperitoneal space and tumor motion of <5 mm.
2. Adolescents with diaphragmatic tumor motion exceeding 10 mm require special attention, because significant declines in target coverage and dose homogeneity were seen in simulated treatments of such patients.

MRI for detecting changes in proton ranges during treatment courses

Sharp dose fall-off of proton fields make proton range and resultant radiation dose sensitive to anatomic changes during the RT course.

We demonstrated the feasibility of using MRI, as an alternative to CT or CBCT, for accurately detecting changes in proton ranges.

Procedure for MRI-based estimation of water equivalent path length and its evaluation demonstrated with images of an example patient.

Summary and future outlook

• We performed >500 pediatric MRI studies (treatment planning and on-therapy monitoring) in the first year after installing Philips Ingenia MRI systems.

• Having direct access to dedicated MRI systems has greatly facilitated our visualization of tumors and surgical cavities at the time of RT.

• Patient imaged in treatment positions with coils in RT configurations can yield images of good quality suitable for RT planning.

• We anticipate MR applications to further expand to image guidance, delineating subvolumes with high tumor burdens, and predicting treatment response.
Thank you for your time!

We acknowledge support from our institution and Philips in implementing MRI for RT.

Contact: chia-ho.hua@stjude.org
A partner for integrating solutions

Ingenia MR-RT